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Smart structures: Part I—Active and semi-active control

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Abstract This paper and a companion paper present a state-of-the-art review of significant research performed in the area of smart structures. The focus of the review is journal articles published since 1997. This paper reviews articles on active and-semi active control of structures using a variety of systems. Active control systems include active tuned mass dampers, distributed actuators, active tendon systems and active coupled building systems. Semi-active control systems include: magnetorheological (MR) fluid dampers, semi-active stiffness dampers, semi-active tuned liquid column dampers, and piezoelectric dampers. A review of hybrid control systems and control strategies is presented in the companion paper.

Contents

1. Introduction

What is a smart or adaptive structure? Broadly speaking, a smart structure can sense its dynamic loading environment via sensors and modify its behavior in real time, so that it can withstand external dynamic forces, such as earthquake loading, wind or impact. In other words, a smart structure is an intelligent machine that can change and adapt to its environment dynamically [1,2]. This is in contrast to the conventional view of a structure that has existed for millennia [3–5]. There has been increasing interest in the field of smart structures in the past twenty years. This is definitely one of the most exciting areas of research in structural engineering. Many workers in the field are multidisciplinary, forward thinking and out-of-the-box researchers. The goal of this and the companion paper [6] (this issue) is to review the significant research done in this area in recent years.

How can we make a structure smart? There are different strategies. The strategy pursued and advocated by the senior author and his associates over the past 15 years is to place actuators within the structure, strategically, which will apply

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the required forces to compensate for the forces of nature and minimize the vibrations of the structure [7]. In other words, in an adaptive/smart structure, we design a predetermined number of members to be actively controlled members. Each such member has a sensor, a feedback control device [8–10] and an actuator. The sensor measures the displacements along the degrees of freedom. The feedback control device determines the appropriate correction to the uncontrolled response, and the actuator applies the required force. Such a system consists of three physical components: sensors, actuators and a computer. There is also the need for a control algorithm that will determine the magnitude of control forces at any given time. However, there are other strategies and physical systems. The common goal in them all is to minimize the vibrations in real time. All of them require an effective control algorithm.

Housner et al. [11] presented a thorough review of the field of structural control up to 1996. While the topic of smart structures is broader than structural control, they reviewed many of the papers published on the subject. The scope of the present review is limited primarily to journal articles published since 1997.

A host of engineers are working in the area of smart structures including mechanical, electrical, materials and structural engineers. As such, the field of smart structures can be quite broad and multidisciplinary [12–31]. It can also include the field of smart materials. In order to limit the scope of this review within the limitations of a journal article, it has been limited mostly to civil structures, with only mention of relevant papers on smart materials. The review is presented in two companion articles. This article is devoted to the review of papers published on active and semi-active control of structures. It is presented roughly in chronological order. Hybrid control systems and control strategies are reviewed in the companion paper [6] (this issue).

2. Active control of structures

2.1. Active tuned mass damper

Tuned Mass Dampers (TMD) have fixed frequency and damping characteristics and can be used to tune only a given fixed frequency of vibration, normally the fundamental frequency of vibrations of a structure [32]. TMD systems were developed as an innovative system for passive vibration control of building structures in the 1970's. Since then, they have been implemented in a number of high-profile highrise buildings. The first building in the US to be designed with a TMD from the beginning appears to be the 70-story Park Tower in Chicago completed in 2000. The world's second tallest building, Taipei 101, also employs a TMD system with a 660 metric ton steel pendulum used to offset the lateral displacements of the building caused by strong wind gusts. Despite the emergence of nearly four decade-old technology in practice, as a technological marvel, TMD systems have several shortcomings. First, it is not possible to calculate the fundamental frequency of vibration of a structure accurately. Second, this frequency changes during an extreme dynamic event, such as strong ground motion. TMD systems can be partially effective when the fundamental frequency of the structure dominates the response, which may be the case for vibrations under ordinary winds. TMD systems are not as effective for irregular structures under strong ground motion, when several different modes of vibration may contribute significantly to the dynamic response of the structure.

One of the earliest approaches to active control of vibrations in structures has been Active Tuned Mass Damper (ATMD) systems. This system is also known as an Active Mass Driver (AMD). In an ATMD system, an actuator placed between the structure and the TMD system applies a computed force in real time. Wu and Yang [33] discuss the use of an ATMD system consisting of three actuators to control the wind-induced motion of the 310-m Nanjing TV transmission Tower in China. For the control algorithm, they used the Linear Quadratic Gaussian (LQG), $H\infty$, and continuous Sliding Mode Control (SMC) strategies, and found that all three performed well at mitigating the vibration of the structure. (For a brief description of various control strategies, refer to [6] (this issue).) Yan et al. [34] present expressions for the required control force to be applied by an ATMD system for a high-rise building with a rectangular plan subjected to vibrations due to wind loadings.

Yamamoto et al. [35] present the performance results of ATMD systems installed in four actual steel-frame high-rise buildings in Japan, ranging in height from 58.0 to 189.7 m (11–34 stories). The ATMD systems for three of the buildings utilized existing masses, such as ice thermal storage tanks (used for air conditioning) and a heliport as the controlling masses. To verify the control systems, they carried out forced vibration tests on each building before completion, using the ATMD system itself to shake the building. After the ATMD system shook the building for a period of 10 s, it was activated to suppress the response of the building. The authors also monitored the response of the completed buildings under minor seismic events and wind loading. Their results showed that the installed ATMDs were effective at controlling the response of the buildings.

Li et al. [36] use the H_2 control algorithm to manage the response of a two-dimensional (2D) model of a jacketed-type offshore platform in 218 m of water, equipped with an ATMD, and subjected to wave loadings. They found that an ATMD system performs better than a passive TMD system. Lee and Wang [37] examine the effect of pitch width (the distance between threads) on the efficiency of an ATMD system, utilizing a servomotor and ball screw to control a 2D five-story frame. The ball screw is driven by the servomotor and advances the mass one pitch width per revolution through a nut. Friction between the ball screw and nut is minimized by using metal bearing balls that are sized to fit the ball screw precisely. The authors use an optimal direct output feedback strategy where "*output measurement is directly multiplied by time-invariant feedback gain and fed back to the structural system*" [38] and the 1940, El Centro, California earthquake as input. They found that if pitch is adjusted correctly, a 70% reduction in peak response is possible. Conversely, if the pitch is not adjusted correctly, the ATMD system may have a detrimental effect on the structure. The authors claim that this high performance, along with the minimal noise output and lack of oil leakage, make this type of ATMD more desirable than ATMD systems driven by actuators.

The majority of research published on TMD systems is limited to a single ATMD. A few researchers have advocated the use of multiple ATMDs in a given structure. Ikeda et al. [39] discuss the performance of an ATMD system actually installed in a ten-story, steel-frame building in Tokyo in 1989. The system utilizes two AMTDs to control both lateral and torsional vibrations and the LQR control algorithm. Since its installation, the building has been subjected to actual earthquake and typhoon wind loadings, with 26% and 11% reductions in lateral and torsional vibrations during earthquakes, and a 33% reduction in peak response due to wind loadings.